The masses of $P_c^*(4380)$ and $P_c^*(4450)$ in the quasi particle diquark model

R.Ghosh[1], A. Bhattacharya [2], B.Chakrabarti*

[1,2] Department of Physics, Jadavpur University Kolkata-700032, India.

*Department of Physics, Jogamaya Devi Collage Kolkata, India.

E-mail: [2]pampa@phys.jdvu.ac.in, *$ballari_$chakrabarti@yahoo.co.in

The masses of the recently reported by LHCb two pentaquark charmonium states $P_c^*(4380)$ and $P_c^*(4450)$ which are supposed to have the configuration ($uudc\bar{c}$) have been estimated in the framework of the quasiparticle model of diquarks considering $[ud][uc]\bar{c}$ configuration. The masses are reproduced very well which indicates that the description of diquark as quasiparticle is very useful for describing multiquark state and to understand the dynamics of it.

PACS No.:14.20Lq, 14.20.Mr, 12.38.Ge, 14.20.-c

Recently LHCb[1] has reported the existence of pentaquark charmonium states with the decay of Λ_b^0 ($\Lambda_b^0 \rightarrow J\psi K^- p$). The intermediate states have been identified as $P_c^*(4380)$ and $P_c^*(4450)$. The states are identified as sum of two up quarks, one down quark, one charm quark and one anti-charm quark with spin $\frac{3}{2}$ and $\frac{5}{2}$ respectively. The identification of these pentaquark states is exciting and will give new impetus to the study of the properties and dynamics of multiquark states [2]. The pentaquarks are usually described as diquark-diquark-antiquark configuration [3,4]. The diquarks which are supposed to be highly co-related antisymmetric coloured object are one of the important candidate for study of the exotic particles as well as usual baryons. A number of models have been suggested for diquark [3-10]. In the present work we have studied the recently identified P_c^* states in diquark-diquark-antiquark configuration in the framework of quasiparticle model of diquark suggested by us [10-12].

Recently we have suggested a model for diquark in which two quarks are assumed to be correlated to form a low energy configuration [10-12]. Diquarks are supposed to behave like

a quasi particle in an analogy with an electron in the crystal lattice which behaves as a quasi particle [13]. It is well known that a quasi particle is a low-lying excited state whose motion is modified by the interactions within the system. An electron in a crystal is subjected to two types of forces one is the effect of the crystal field (-∇V) and the other is external force (F) which accelerates the electron [14]. Under the influence of these two forces, it behaves like a quasi particle having velocity v whose effective mass m^* reflects the inertia of electrons in a crystal field and can be represented as [13]:

$$m^* \frac{dv}{dt} = F \tag{1}$$

The bare electrons (with normal mass m) are affected by the lattice force -∇V and the external force F so that:

$$m \frac{dv}{dt} = F - \frac{dV}{dx} \tag{2}$$

From (1) and (2) the ratio of the normal mass (m) to the effective mass (m^*) can be represented as:

$$m/m^* = 1 - \frac{1}{F}[\frac{\delta V}{\delta x}] \tag{3}$$

The difference between the effective and normal mass is attributed to the lattice force. The sign of its average m^* can be less or greater than 'm' or even negative according to the sign of the potential. An elementary particle in vacuum may be suggested to be in a situation exactly resembling that of an electron in a crystal [14]. We have proposed a similar type of picture for the diquark as a quasi particle inside a hadron. We have assumed that under the combined force of confinement and asymptotic freedom a diquark in hadron behaves like a quasi particle and its mass gets modified simulating the many body interaction in a hadron. The potential V $=\frac{2}{3}\frac{\alpha_s}{r}$ (where α_s is the strong coupling constant) is assumed to resemble the crystal field on a crystal electron and is positive for resonance state [13]. On the other hand an average force F = -ar resembles the external force where 'a' is a suitable constant. The potential can be represented as:

$$V_{ij} = \frac{\alpha}{r} + (F_i.F_j)(-\frac{1}{2}Kr^2) \tag{4}$$

Where the coupling constant α=(2/3)α_s,$F_i.F_j$=-(2/3), K is the strength parameter. Hence V_{ij} may be represented as:

$$V_{ij} = \frac{(2/3)\alpha_s}{r} + ar^2 \quad (5)$$

Where a=K/3.

The ratio of the constituent mass and the effective mass of the diquark (m_D) has been obtained following equation (3) as,

$$\frac{m_q + m_{q\prime}}{m_D} = 1 - \frac{\alpha_s}{3ar^3} \quad (6)$$

here $m_q + m_{q\prime}$ represents the normal constituent mass of the diquark, m_D is the effective mass of the diquark and 'r' is radius parameter of diquark. With α_s= 0.2 [15], a = 0.02 GeV^3[14], r_{ud}(scalar)= 0.98fm [5], r_{ud} (vector)= 0.8fm[16], r_{uc}(scalar)= 1.1fm[17],r_{uc}(vector) = 0.861fm [5], m_u=m_d= 0.360 GeV [4] and m_c= 1.55 GeV [18] we have estimated the masses of the diquarks in the framework of the quasi particle model [14]. We have obtained the diquark mass values as m_{ud} = 0.763 GeV, m_{uc} = 1.989 GeV for scalar diquarks and m_{ud}= 0.803 GeV, m_{uc} = 2.084 GeV for vector diquark. It is interesting to observe here that simulating the many body interaction the effective mass of the diquark becomes greater than the constituents.

The mass formula of the pentaquark state can be expressed with relevant diquark-diquark-antiquark configuration as,

$$M = m_{D_1} + m_{D_2} + m_{\overline{q}} + E_S \quad (7)$$

where m_{D_1}, m_{D_2} are diquark masses, $m_{\overline{q}}$ is the antiquark mass and E_S is spin term and expressed as [19,20]:

$$E_S = \frac{8}{9}\frac{\alpha_S}{m_1 m_2}\vec{S}_1 \cdot \vec{S}_2 |\psi(0)|^2 \quad (8)$$

where the strong interaction constant α_S = 0.2 [15] and $\vec{S}_1 \cdot \vec{S}_2$ is the spin interaction of corresponding states. The masses have been estimated using the relation (7) and displayed in Table I.

Table I: Mass of pentaquark charmonium states:

Pentaquark charmonium state	*Quark Content*	*Experimental Mass*[1] *(MeV)*	*Our Work (MeV)*
$P_c^*(4380)$	$[ud]_0[uc]_1\overline{c}$	4380 ± 8	4400
$(spin\frac{3}{2})$	$[ud]_1[uc]_0\overline{c}$	± 29	4345
$P_c^*(4450)$	$[ud]_1[uc]_1\overline{c}$	4449.8 ± 1.7	4443
$(spin\frac{5}{2})$		± 2.5	

In the present work we have estimated masses of the particles $P_c^*(4380)$of spin $\frac{3}{2}$ in both $[ud]_0[uc]_1\overline{c}$ and $[ud]_1[uc]_0\overline{c}$ configurations and have obtained the masses as 4403 MeV and 4345 MeV respectively. The $P_c^*(4450)$ of spin $\frac{5}{2}$ has been estimated in the pentaquark configuration of $[ud]_1[uc]_1\overline{c}$ and obtained the mass as 4443 MeV. The results are found to be in very good agreement with experiment. In the current work it is observed that the description of pentaquark as diquark-diquark-antiquark picture with diquark as quasi particle reproduces the observed mass of intermediate state very well. It is interesting to observe that the contribution from vacuum can be simulated as effective mass approximation for diquark whose effective mass is more than the constituents and in excited state. The experimental identification of pentaquark is long awaited. In our present investigation the mass of $P_c^*(4380)$ and $P_c^*(4450)$ have been described in quasiparticle picture of 'diquark'. We will also study the particles as baryon-meson system and also in composite fermion model of diquark in our future work. The current investigation has immense importance in the understanding of quark dynamics in multiquark system and found to be very useful and prospective.

Acknowledgments :

Authors are thankful to University Grants Commission, New Delhi, India for their financial supports.

References:-

[1] R. Aaij, B. Adeva, M. Adinolfi, A. Affolder, Z. Ajaltouni, S. Akar, J. Albrecht, F. Alessio, M. Alexander, S. Ali et al, (LHCb Collaboration), arXiv:1507.03414v1[hep-ex] (2015).

[2] M. Gell-Mann, Phys. Lett. **8**, 214 (1964).

[3] R. L. Jaffe and F. Wilczek, Phys. Rev. Lett. **91**, 232003 (2003).

[4] M. Karlinar and H. Lipkin, Phys. Lett. B **575**, 294 (2003).

[5] A. S. de Castro, H. F. de Carvalho and A. C. B. Antunes, Z. Phys. C **57**, 315 (1993).

[6] M. Anselmino, E. Predazzi, S. Ekelin, S. Fredriksson and D. B. Lichenberg, Rev. Mod. Phys. **65**, 1199 (1993).

[7] T. Schafer and E. Shuryak, Rev. Mod. Phys. **70**, 323 (1998).

[8] R. G. Betman and L. V. Laparashvili, Sov. J. Nucl. Phys. **41**, 295 (1985).

[9] E. V. Shuryak, Nucl. Phys. B **203**, 93 (1982); E. V. Shuryak and I. Zahed, Phys. Lett. **589**, 21 (2004).

[10] A. Bhattacharya, A. Sagari, B. Chakrabarti and S. Mani, Phys. Rev. C **81**, 015202 (2010).

[11] A. Bhattacharya, B. Chakrabarti, A. Sagari and S. Mani, Int. J. Theo. Phys. **47**, 2507 (2008).

[12] A. Bhattacharya, A. Chandra, B. Chakrabarti and A. Sagari, Eur. Phys. J. Plus. **126**, 57 (2011).

[13] A. Haug, *Theoretical Solid State Physics* (Pergamon Press,1975),Vol.1, p.100 .

[14] B. Chakrabarti, A. Bhattacharya, S. Mani and A. Sagari, Acta. Phys. Polo. B**41** 95 (2010).

[15] W. Lucha, F. F. Scholberl and d. Gromes, Phys. Rep. **200**, 168 (1991).

[16] K. Nagata and A. Hosaka, Ann. Rep./2006/Sec 2/nagata.pdf.

[17] B. Chakrabarti, Mod. Phys. Lett. A **12**, 2133 (1997).

[18] Griffiths, David, *Introduction to Elementary Particles* (WILEY-VCH, 2008) p.135.

[19]. A.Bhattacharya, B. Chakrabarti, T. Sarkhel and S. N. Banerjee, Int. J. Mod. Phys. A **15**, 2053 (2000).

[20]. A. Bhattacharya, B. Chakrabarti and S. N. Banerjee, Eur. Phys. J. C **2**, 671 (1998).